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Preliminary Numerical Study on TRID System for Flutter Vibration Control of Bridge Structure

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Abstract

Based on the recently proposed innovative Tuned Rotary Inertia Damper (abbreviated as TRID) control system, the possibility of its application for the wind induced flutter vibration control of long span bridge structure is discussed in this paper. Firstly, the background and current methods for wind induced flutter vibration control of bridge structures are summarized. Then, equations of motion of the bridge segment model are developed based on the classical Lagrange principle, and the critical wind speed of flutter vibration of Humen Bridge is solved using both Scanlan and state space based methods. Furthermore, the TRID control system is incorporated into the system model, where the TRID inertia mass can be physically installed between connections of consecutive bridge deck sections. Optimal parameters of TRID control system and their interactions, i.e. tuning frequency ratio, damping ratio and rotary inertia ratio, are analyzed through numerical approaches. Based on thorough numerical analysis, the results show that the TRID control system is feasible and effective on enhancing the flutter vibration stability of long span bridge structures, e.g. the ultimate critical wind speed of the illustration can be increased by 10% at the cost of adding an additional 5% rotary inertia to the bridge structure.

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Keywords: *Flutter vibration control; tuned rotary inertia damper; bridge deck; long span bridge structure; parameter optimization; dynamic interactions*

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The famous Tacoma bridge collapsed due to a strong wind gust attack in July 1940, when the wind speed was just about 18m/s. Thereafter, people started to notice the importance of bridge flutter vibration problems, and bridge wind engineering formally began to become a new research area within Civil Engineering discipline. Generally speaking, the wind effects on structures can be attributed to some kind of fluid-solid interactions. This paper discusses the innovative control method of wind excited bridge flutter vibration, which relates both wind loads and structural response, from the perspective view of control structure interactions.

According to traditional classifications, the flutter vibration mode is caused by self-excitation force from average wind loads. Sometimes, flutter vibration is diverge structural response and may result in collapse of a total bridge structure. According to the current design method and practice, some measures must be incorporated into the bridge structure if the flutter critical wind speed is lower than the examining wind speed. Normally this kind of measures includes changing the aerodynamic property of structure, i.e. to modify outlines of bridge decks and etc. However, for long span and ultra long span bridges, only such kind of method is not enough and additional measures should be developed.

By means of adding a mechanical element, i.e. tuning its frequency in resonance with the main structure and absorbing vibration through energy dissipation becomes an attractive and promising trend in this research field recently. For example, TMD (Tuned Mass damper) control system has been proposed for wind induced flutter vibration control of various civil engineering structures including bridge deck structures and bridge tower mast structures for several years. Thereafter, DTMD (distributed Tuned Mass Damper system) and MTMD (multiple Tuned Mass Damper) control system have been proposed and studied for the similar problem, respectively. However, there are some unavoidable drawbacks of the currently known passive control systems for flutter vibration control of bridge structure. For example, TMD system can only be effective on suppressing linear motion of bridge decks, e.g. vertical vibration. Although DTMD can be used for torsion vibration control of bridge decks, its effectiveness is quite amplitude dependent and can be sharply decreased with the increasing of flutter induced vibration amplitudes of bridge, due to its intrinsic linear working mechanism (Zhang etal., 2008, 2009). Based on the innovative concept of Tuned Rotary Inertia Damper (abbreviated as TRID) control system proposed by Zhang etal. (2007b), the possibility of its application for wind induced flutter vibration control of long span bridge deck structures is studied in this paper. Similar to traditional TMD control system, the mechanism of TRID system onto the bridge structure can be briefly attributed to three aspects: 1) to increase the rotary inertia of the original bridge deck segment; 2) to increase the total excitation force onto the original system through increasing total inertia; 3) to impose additional control force onto the bridge deck structure passively.

2. Theoretical foundations and modeling development

The piece segment model of one typical bridge structure is considered in the following analysis. Figure 1 shows the structural calculation model within a uniformed wind inflow in a 2D dimension plane. Scanlan *etal.* (1993) have given the expression of flutter vibration induced self excitation force with 2 degree of freedom based on 8 aerodynamic derivatives.

$$L = \rho U^2 B[KH_1^* \frac{\dot{h}}{U} + KH_2^* \frac{B\dot{\alpha}}{U} + K^2 H_3^* \alpha + K^2 H_4^* \frac{h}{B}] \tag{1a}$$

$$M = \rho U^2 B^2 [K A_1^* \frac{\dot{h}}{U} + K A_2^* \frac{B\dot{\alpha}}{U} + K^2 A_3^* \alpha + K^2 A_4^* \frac{h}{B}] \tag{1b}$$

Where ρ is the mass density of inflow, normally $\rho = 1.225 \mathrm{kg/m^3}$; L and M are self excitation aerodynamic lifting force (N) and moment of torque ($\mathrm{N \cdot m}$), respectively; B is the width of bridge deck; U is the average wind speed; $K = B\omega / U$ is the conversion frequency; ω is the circular frequency; A_i^* and H_i^* (i=1~4) are flutter derivatives of girder section, which are all non-dimensional function of K.

The sketch of the cross section of bridge deck with added TRID control system is shown in Figure 2. The cross section of the control system is simple and rather small relative to the cross section of bridge deck, and all the above mentioned aerodynamic derivatives are assumed to be unchanged whatever the mass ratio of TRID system over bridge structural segment, or rotary inertia ratio of TRID system over that of the bridge structure, respectively.

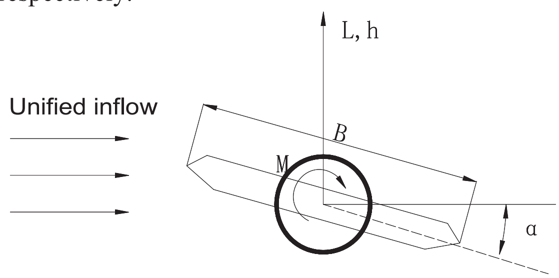
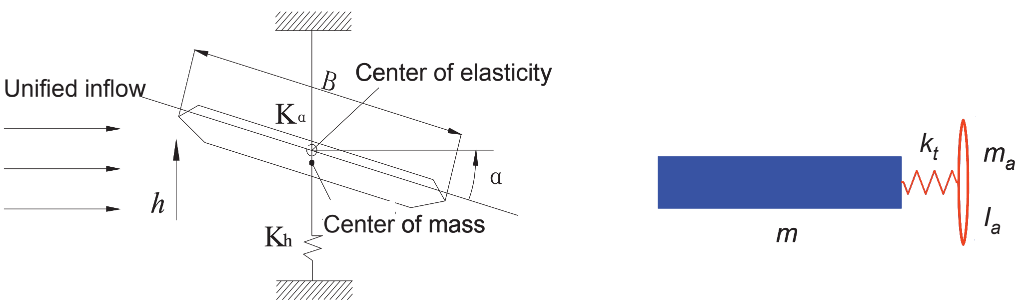


Figure 1: Two dimensional bridge structural segment model within uniformed inflows.



(a) cross section view (b) side view

Figure 2: Sketch of TRID control system and the bridge segment model.

As shown in Figure 2, kinetic energy of unit length of bridge structure can be expressed as:

$$T = \frac{1}{2}(m + m_a)\dot{h}^2 + \frac{1}{2} I \dot{\alpha}^2 + \frac{1}{2} I_a \dot{\phi}^2 \tag{2}$$

Potential energy of each unit length of bridge structure is:

$$V = \frac{1}{2}k_h h^2 + \frac{1}{2}k_\alpha \alpha^2 + \frac{1}{2}k_t(\phi - \alpha)^2 \tag{3}$$

According to the Lagrange principle, the equation of motion for TRID controlled bridge segment structural model is developed. Detailed procedures can be found in Li (2009), and the achieved final flutter vibration equation of the system can be expressed as:

$$(m + m_a)(\ddot{h} + 2\xi_{h0}\omega_{h0}\dot{h} + \omega_{h0}^2 h) = \frac{1}{2}\rho U^2(2B)[KH_1^* \frac{\dot{h}}{U} + KH_2^* \frac{B\dot{\alpha}}{U} + K^2 H_3^* \alpha + K^2 H_4^* \frac{h}{B}] \tag{4a}$$

$$\begin{aligned}(I + I_a)(\ddot{\alpha} + 2\xi_{\alpha0}\omega_{\alpha0}\dot{\alpha} + \omega_{\alpha0}^2 \alpha) &= k_t(\phi - \alpha) + C_t(\dot{\phi} - \dot{\alpha}) \\ &+ \frac{1}{2}\rho U^2(2B^2)[KA_1^* \frac{\dot{h}}{U} + KA_2^* \frac{B\dot{\alpha}}{U} + K^2 A_3^* \alpha + K^2 A_4^* \frac{h}{B}]\end{aligned} \tag{4b}$$

$$I_a \ddot{\phi} = -k_t(\phi - \alpha) - C_t(\dot{\phi} - \dot{\alpha}) \tag{4c}$$

Where m and I are mass ($\mathrm{kg/m}$) and rotation inertia ($\mathrm{kg \cdot m}$) of each unit length of the deck model structure, respectively. m_a and I_a are mass ($\mathrm{kg/m}$) and rotary inertia ($\mathrm{kg \cdot m}$) of TRID system, respectively. ξ_{h0} and $\xi_{\alpha0}$ are damping ratio of structural vertical motion and torsion motion, respectively. ω_{h0} and $\omega_{\alpha0}$ are circular frequency of structural vertical motion and torsion motion, respectively. k_t and C_t are coefficients of stiffness and damping of TRID control system, respectively.

3. Solution methods

State space based method is widely used in the flutter vibration analysis of long span bridge structures. The corresponding differential equation of motion for the system can be expressed as

$$[M]\{\ddot{X}\} + [C]\{\dot{X}\} + [K]\{X\} = \{0\} \tag{5}$$

$$[C] = [C_s] - [C_{se}] \text{ and } [K] = [K_s] - [K_{se}] \tag{6}$$

Where $[M]$ is the general system (structure and TRID control system) mass matrix, $[C]$ is the general system damping matrix, $[K]$ is the general system stiffness matrix, $[K_{se}]$ is the aerodynamic stiffness matrix due to flutter vibration induced self excitation, $[C_{se}]$ is the aerodynamic damping matrix due to flutter vibration induced self excitation, $[K_s]$ is the general aerodynamic stiffness matrix of bridge structure, and $[C_s]$ is the general aerodynamic damping matrix of bridge structure.

Assuming the general form of analytical solution of the differential equation of motion (5) for the system is

$$\{X\} = \{\Phi\}\exp(\lambda t) \tag{7}$$

Substituting equation (7) into equation (5), then

$$(\lambda^2[M] + \lambda[C] + [K])\{\Phi\}\exp(\lambda t) = \{0\} \tag{8}$$

Where λ is the eigenvalues of the general system, $\{\Phi\}$ is the eigenvectors corresponding to the eigenvalues.

Because $\{\Phi\}\exp(\lambda t)$ is a non zero item, moreover, if the nontrivial solutions for equation (8) is needed in the analysis, the coefficients matrix within the round brackets part of equation (8) should be a singular matrix, then

$$\det(\lambda^2[M]+\lambda[C]+[K])=0 \tag{9}$$

In order to convert the above second order problem into a linear case, the auxiliary equation should be introduced as

$$[M]\{\dot{X}\}-[M]\{\dot{X}\}=\{0\} \tag{10}$$

Therefore, the matrix form of equation (5) and equation (10) can be expressed as

$$\begin{bmatrix} [C] & [M] \\ [M] & [0] \end{bmatrix}\begin{Bmatrix} \dot{X} \\ \ddot{X} \end{Bmatrix}+\begin{bmatrix} [K] & [0] \\ [0] & -[M] \end{bmatrix}\begin{Bmatrix} X \\ \dot{X} \end{Bmatrix}=\begin{Bmatrix} \{0\} \\ \{0\} \end{Bmatrix} \tag{11}$$

Let $\{q\}=[X \quad \dot{X}]^T$, then the state space based equations can be expressed as

$$[A]\{\dot{q}\}+[B]\{q\}=\{0\} \tag{12}$$

Where

$$[A]=\begin{bmatrix} [C] & [M] \\ [M] & [0] \end{bmatrix},\ [B]=\begin{bmatrix} [K] & [0] \\ [0] & -[M] \end{bmatrix},\ [M]=\begin{bmatrix} m+m_a & 0 & 0 \\ 0 & I+I_a & 0 \\ 0 & 0 & I_a \end{bmatrix} \tag{13}$$

$$[C]=\begin{bmatrix} 2(m+m_a)\xi_{h0}\omega_{h0}-\rho B^2\omega H_1^* & -\rho B^3\omega H_2^* & 0 \\ -\rho B^3\omega A_1^* & 2(I+I_a)\xi_{\alpha 0}\omega_{\alpha 0}-\rho B^4\omega A_2^*+C_t & -C_t \\ 0 & -C_t & C_t \end{bmatrix}$$

$$[K]=\begin{bmatrix} (m+m_a)\omega_{h0}^2-\rho B^2\omega^2 H_4^* & -\rho B^3\omega^2 H_3^* & 0 \\ -\rho B^3\omega^2 A_4^* & 2(I+I_a)\omega_{\alpha 0}^2-\rho B^4\omega^2 A_3^*+k_t & -k_t \\ 0 & -k_t & k_t \end{bmatrix}$$

Let $\{X\}=\{\Phi\}\exp(\lambda t)$, and finally the equation of a nonsymmetrical generalized linear eigenvalue problem can be achieved as

$$[A]\lambda\{x\}+[B]\{x\}=\{0\} \tag{14}$$

Where $\{x\}=\left[\{\Phi\} \quad \lambda\{\Phi\}\right]^T$.

Solving the nonsymmetrical generalized eigenvalue problem of equation (14), $m+N$ pieces of eigenvalues and their corresponding eigenvectors with positive imaginary parts can be achieved as

$$\lambda_i=(-\xi_i+i)\omega_i,\quad \{\Phi\}_i=\{\alpha+i\beta\}_i \quad (i=1,2,...m+N) \tag{15}$$

With the increasing of wind speed, if the real part of any of the system eigenvalues changes from negative values into positive values, then the condition of critical wind speed is achieved. The flutter vibration will occur and may result in destroy of the bridge structure due to divergence of dynamic response, where amplitudes ratio of each parametric modal and phase relations can be formulated according to corresponding eigenvectors.

4. Numerical example and analysis

In this section, the Humen bridge is chosen as an illustration example for numerical analysis. The bridge locates within the seaport of Zhujiang River in Guangdong province in China, which is a key hinge within the highway transportation system linking Guangzhou, Shenzhen and Zhuhai cities. The Humen bridge structure is a suspension bridge with the main span of 888 meters. The girder (deck) of the bridge is streamline shaped with a flat steel box beam section, and the girder width is 35.6 meters and the height is 3.102 meters, and the spacing distance of main cable is 33 meters. The main tower is a gate-shaped rigid steel frame structure. The Theodorson theory is introduced in the aerodynamic analysis of flat plate response of the girder structure. The results show that the dominant flutter vibration modes of the structure are the first order torsion motion along the longitudinal axis of the bridge deck structure and the first order bending vibration in vertical direction, respectively.

Table 1: Structural parameters of the Humen bridge

B(m)	m(kg/m)	$I(\text{kg}\cdot\text{m})$	f_h(Hz)	f_α(Hz)	ξ_h	ξ_α
35.6	18.3×10^3	2.09×10^6	0.1117	0.3612	0.005	0.005

The analytical model of coupled flutter vibration is considered in the following analysis. Several parameters are defined, $\mu = I_a / I$ is the rotary inertia ratio, $\omega_a = \sqrt{k_t / I_a}$ is the natural frequency of TRID control system, $\xi_a = C_t / (2 I_a \omega_a)$ is the damping ratio. When studying the influence of TRID frequency on the control effectiveness, non dimensional unified frequency tuning ratio η is defined as $\eta = \omega_a / \omega_0$, where ω_a is the circular frequency of TRID system, and ω_0 is the flutter vibration frequency of the uncontrolled segment bridge model.

Table 2: Comparison on uncontrolled indexes by 5 approaches

	Critical wind speed of flutter vibration （m/s）	Circular frequency of flutter vibration（rad/s）
Scanlan method	86.37	1.5071
M-S method	86.54	1.5025
Ding Quanshun	86.54	1.5025
State space method	86.55	1.5024
Subspace complex eigenvalues method	86.54	1.5025

As given in the above table, the results from the last four methods are basically the same, where the difference is parameter simplification approaches during the calculation process. Based on the comparison of uncontrolled results, the relative error is shown to be small through different approaches, thus only the Scanlan and state space based methods will be used in the following analysis and comparison. As shown in table 2, the critical circular frequency of flutter vibration is 1.5025 rad/s, which falls between the structural first order of torsion motion and the first order of vertical bending vibration. Based on the results of energy distribution, a bigger portion is shown to be existing in the torsion vibration mode. This provides the foundation of utilizing TRID control system for energy dissipation through relative rotation between the bridge deck structure and the control system, *i.e.* dynamical interactions.

4.1. Simulation results

In the following, several primary parameters of TRID control system, such as frequency tuning ratio, damping ratio and rotary inertia ratio etc. and their interactions as well as influence on control effectiveness are analyzed, respectively.

4.1.1. Impact of rotary frequency tuning ratio

The range of rotary frequency tuning ratio is selected to be the non dimensional unified values, from zero to 2.3, where the impact of TRID system is shown to be relatively stable. Three different damping ratio cases, 5%, 8% (approximate the optimal value according to the classical passive frequency tuning and energy absorbing control theory) and 13.36%, are selected for comparison, where the mass ratio of TRID system is 1% and the rotary inertia ratio is 5%. Results are given in Figure 3.

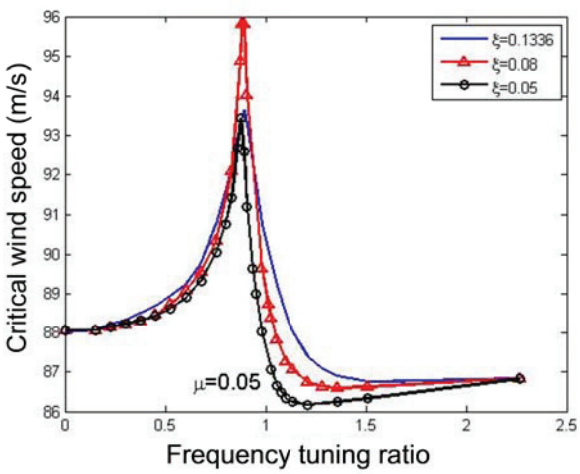


Figure 3: Relation between tuning frequency ratio of TRID system and critical wind speed.

From the above figure, although with different damping ratios, the flutter critical wind speed of bridge structure is shown to be increased when the TRID control system is tuned a little bit lower than the natural frequency of structure. For example, when the mass ratio of TRID system is 1% and rotary inertia ratio is 5%, the optimized frequency tuning ratio is shown to be about 88% and the maximum critical wind speed can be increased by about 10.7%. The results achieved here are quite attractive and promising for utilizing TRID control system to enhance the flutter vibration stability of long span bridge structures.

4.1.2. Impact of damping ratio

Under different damping ratios, the critical wind speeds increase at first and then decrease, which indicates an optimal damping ratio exists for the TRID control system. Since there are three types of force provided by the TRID system, *i.e.* the inertia torque of moment, the restoring torque of moment and the damping torque of moment, the combined effects of these three items become the final control force imposed onto the bridge structure. It is quite complicated interaction and energy transferring process among the three force items (Zhang and Ou, 2007a). For example, if the damping ratio is too high, the rotation of TRID can not be easily excited and the inertia effect will be weakened. Vice versa, if the damping ratio is too low, the restoring force and the inertia force will become dominant which do not necessarily dissipate energy but transferring energy between the main structure and the control system in the form of potential energy and kinetic energy. Similar behavior exists when utilizing Tuned Mass Damper (TMD) system for suppressing structural linear vibrations (Soong, 1997).

Figure 4 shows damping ratio effect of TRID system on enhancing critical wind speed of flutter vibration, under two settings of frequency tuning ratios, 87.6% and 75.5%. Based on the results, the damping ratio is shown to be more sensitive for TRID system when the frequency tuning ratio approaches its optimal value, where the control system is prone to fall within resonance zone with structural vibration which makes the dynamic interactions and energy transferring more intensely.

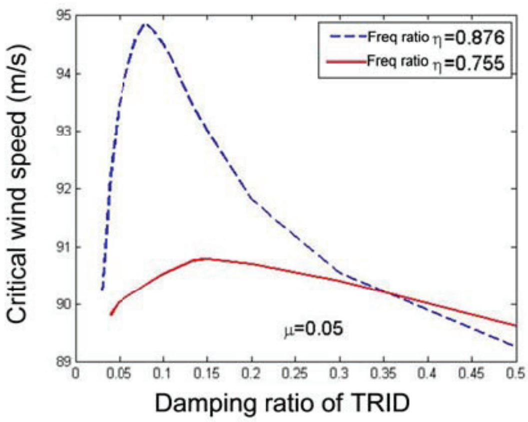


Figure 4: Relation between damping ratio of TRID system and critical wind speed.

4.1.3. Impact of rotary inertia ratio

The rotary inertia ratio is also shown to affect the ultimate critical wind speed of flutter vibration. However, the above three parameters can not be changed at the same time, and the following analysis is carried out on the basis of one is fixed and the other two are varying. Firstly, the damping ratio and frequency tuning ratio are set according to the quasi "optimal" values, and the critical wind speed is shown to be increasing nearly linear with the increasing of rotary inertia ratio, as shown in Figure 5. The bigger inertia effect, the higher control performance will be achieved, however, at the cost of adding in either a bigger physical mass or a huger radius of rotation ring which provides rotary inertia. Then, the relation between the rotary inertia ratio and the quasi "optimal" frequency tuning ratio, as well as the relation between the rotary inertia ratio and the quasi "optimal" damping ratio are analyzed, respectively. The results are given in Figure 6 and Figure 7. Based on these results, the rotary inertia ratio is shown to be inverse proportional to the frequency tuning ratio. To be specific, for a smaller rotary inertia, the TRID control system should be tuned closely with the structure; vice versa, for a bigger rotary inertia, the TRID system should be a little bit under tuned to achieve ideal control effectiveness. The results here validate previous relevant analysis. Bigger inertia requires relative longer time for recovering and restoring, which results in a lower circular frequency of control system. Otherwise, it may cause unavoidable lags into the system dynamical behavior and affect exerting control effect properly. While for the second relation, the rotary inertia is shown to be proportional to the damping ratio under a certain frequency tuning ratio ranges, and bigger damping ratio is actually needed with the increasing of rotary inertia ratio. More relevant results can be calculated based on the established formulations. For example, when the mass ratio of TRID system is 1% and the rotary inertia ratio is 100% (a very big rotation wheel or a ring with big radius is imagined in such case), the ultimate critical wind speed of flutter vibration can be calculated out to be about 146.9007m/s, which is already nearly 70% enhancement as compared with the uncontrolled cases as given in table 2. The corresponding optimal frequency tuning ratio is 78.3%, and the optimal damping ratio is 20%. More details can be found in reference (Li, 2009).

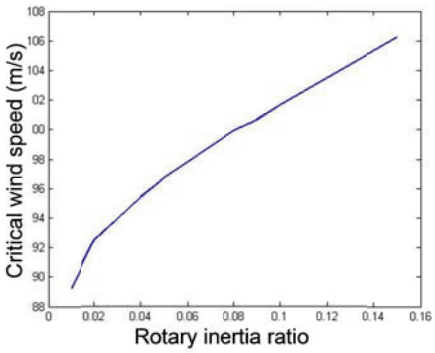


Figure 5: Relation between rotary inertia ratio of TRID system and critical wind speed.

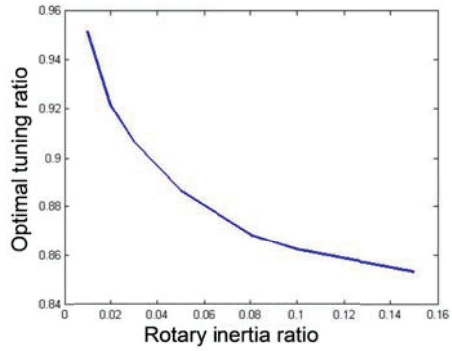


Figure 6: Relation between tuning frequency ratio and rotary inertia ratio of TRID system.

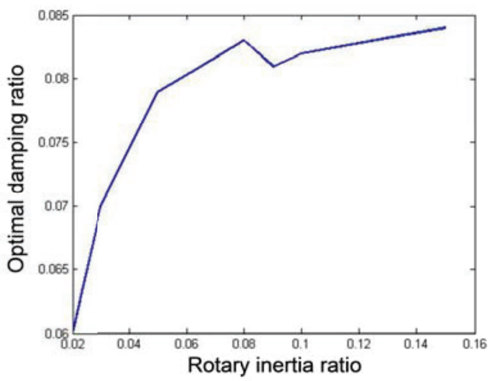


Figure 7: Relation between damping ratio and rotary inertia ratio of TRID system.

5. Conclusions

This paper develops the equations of motion of flutter vibration of long span bridge structure controlled by TRID system. The Humen bridge is selected as a numerical example and the critical wind speed is derived through state space based analytical solution method. Some conclusions can be summarized as:

(1) Through numerical analysis, the TRID control system is shown to be effective on enhancing the flutter vibration stability and the specific results have shown that the ultimate critical wind speed can be increased by 10% at the cost of adding in additional 5% rotary inertia to the bridge structure.

(2) Within the reasonable and acceptable ranges of engineering practice, adding in bigger rotary inertia may contribute to achieve higher critical wind speed of flutter vibration for long span bridge structure.

(3) There are several factors affect the performance of TRID control system, rotary inertia ratio and mass ratio of TRID subsystem, frequency tuning ratio and damping ratio etc. Complicated coupling effects and interactions exist among the these parameters. Preliminary results are presented to illustrate some qualitative influence of TRID system parameters.

The numerical results shown here are quite attractive and promising for utilizing TRID control system to enhance the flutter vibration resultant stability of long span bridge structures.

Acknowledgement

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